Blazars

Marek Sikora* and Greg Madejski†

*N. Copernicus Astronomical Center
00716 Warsaw, Bartycka 18, Poland
†Stanford Linear Accelerator Center
Menlo Park, CA 94025, USA

Abstract. In our review of the blazar phenomenon, we discuss blazar models, with a focus on the following issues: sub-parsec jets and their environment; energy dissipation and particle acceleration; and radiative processes.

INTRODUCTION

Blazars are believed to be a sub-class of radio-loud AGNs with the relativistic jets pointing close to the line of sight, such that the entire electromagnetic spectra are dominated by non-thermal radiation produced in the jets. These spectra usually reveal two broad components, the low energy one - peaking in the IR - to - X–ray range, and the high energy one - peaking in the MeV – TeV range. Both spectral components are variable, particularly strongly in their high energy parts [65,19,69,61,62]. Variability time scales range from years to a fraction of a day, where the rapid variability often takes the form of high amplitude flares. The most extreme events (with the largest amplitude and shortest time scales) have been recorded in γ–ray bands [25,44]. Flares recorded in the GeV and optical bands in high luminosity blazars [68,69] and in the TeV and X-ray bands in low luminosity blazars [41,61,55,50] appear to be correlated. These are most likely produced by the high energy ends of the distributions of radiating particles, and this behavior suggests co-spatial production of high energy and low energy components. The flares are presumably produced in shocks propagating down the jet with relativistic speeds and formed by colliding inhomogeneities [52,57,9,26]. However, present data do not allow us to exclude other possibilities, e.g., production of flares by inhomogeneities flowing through and shocked in the reconfinement regions [34] or via collisions of jets with clouds [16,14].

In any case, the rapid, high amplitude variability events indicate that a significant fraction of the blazar radiation is produced on sub-parsec scales and this provides exceptional opportunity to explore jet properties in the vicinity of the central engine. In order to advance such a study, one must first understand the dominant radiation processes operating in the sub-parsec jets. Until about 10 years ago, the most viable radiation model for relativistic jets was the synchrotron-self-Compton (SSC) model [35,43,28]. According to this model, the smooth, polarized and variable low energy component of blazar spectra is produced by the synchrotron mechanism, while the high energy component results from Comptonization of synchrotron radiation by the same population of electrons which produce the synchrotron component. However, this rather simple picture changed after the discovery of very high and rapidly variable MeV-GeV fluxes in many OVV (optically violent variable) and HP (highly polarized) quasars by the EGRET instrument on the Compton Gamma-Ray Observatory (CGRO): during states of high activity, those were measured to exceed the synchrotron fluxes by a factor 10 or more [67,24], and it was quickly realized that other processes besides SSC can be more important for *gamma*-ray production [15,42,57,8].

Two families of new models emerged, describing the γ–ray production: these were ERC (external-radiation-Compton) and hadronic models. Regarding the external sources of seed soft photons for the inverse-Compton process in the ERC models the following have been suggested: direct disc radiation [15]; BELR (broad-emission-line-region) [57]; disc radiation scattered by the gas surrounding the jet [8]; and jet synchrotron radiation scattered/reprocessed back to the jet by the external gas [27]. In hadronic models, the γ-rays are produced via synchrotron mechanism by secondary electrons which are much more energetic than the electrons accelerated directly. They are injected following hadronic processes and accompanying pair cascades. The primary reaction in hadronic models involves collision of ultra-relativistic protons with soft photons [42] or with the ambient cold protons/ions [2]. The hadronic scenarios, as alternative for the SSC model, have been proposed also to explain TeV radiation, detected by atmospheric Cherenkov detectors in a number of low luminosity BL Lac objects [14,51,1,47].

In our review we discuss: environment of sub-parsec jets in AGNs; dissipation of jet energy and particle acceleration mechanisms; production of non-thermal radiation and blazar models.

SUB-PARSEC JETS AND THEIR ENVIRONMENT

Typical electromagnetic spectrum of luminous "non-blazar" AGNs/quasars consists of three distinctive spectral components: the UV bump and two broad (but less luminous) components, the IR and the X-ray one. In addition, in the optical-UV range, strong, broad emission lines (BEL) are present. UV bumps are produced by central parts of the optically thick accretion disc; X-rays come from hot disc coronae, with possible additions from the base of a jet in radio-loud AGNs [70,31]; near/mid IR radiation presumably comes from dust, located in geometrically thick molecular torus and heated by radiation from the center; and BELs very likely originate in the disc winds, photoionized by UV radiation of an accretion disc [21,46,10,48]. These radiation components form dense radiative environment, through which jets – presumably formed in the vicinity of the central black hole – must pave the way out. Because of Doppler enhancement, the relativistic jets interact most effectively with radiation incident from the front and from side of the jet. At distances where most of blazar non-thermal radiation is produced ($r \sim 10^{17} - 10^{18}$ cm), such radiation is provided by the BEL region and by the hot dust. Energy density of BELs on the jet axis is

$$u_{BEL}(r) \simeq f_1 \frac{L_{BEL}}{4\pi r_{BEL}^2 c} \tag{1}$$

where $r_{BEL} \sim 0.3 L_{UV,46}$ pc [49] and f_1 is the correction function which depends on geometry of the BEL region. If the BEL region forms a narrow torus lying in the disc plane, then

$$f_1 \simeq \frac{1}{1 + (r/r_{BEL})^2} \tag{2}$$

Energy density of dust radiation is

$$u_{IR} \simeq \xi_{IR} \frac{4\sigma_{SB}}{c} T_{dust}^4 \tag{3}$$

where

$$r_{IR} \simeq \sqrt{\frac{L_d}{4\pi\sigma_{SB} T_{dust}^4}} \tag{4}$$

and ξ_{IR} is the fraction of the central engine luminosity L_d reprocessed by hot dust.

If a luminous AGN possess a powerful jet, it is a radio-loud quasar. Observationally, it is classified as OVV/HP quasar if viewed along the jet; as a radio-lobe dominated quasar if viewed at intermediate angles to the jet axis; and as a radio-galaxy with FR II type of large scale radio-morphology (edge brightened lobes with hotspots) if viewed at large angles to the jet axis [29,66]. Much less is known about the sub-parsec environment in very low luminosity AGNs. In particular, the accretion process is less-well understood; we do not know about the radiation efficiency of such objects, and to what extent optically thick plasma participates in the radiation processes. The low luminosity radio-loud AGNs are often accompanied by strong jet activity. The objects with jets pointing away from the line of sight are most likely FR I type radio galaxies with radio morphology characterized by edge darkened extended radio structures. FR I radio galaxies probably form the parent population for BL Lac objects [29,66], which, in similarity to the OVV/HP quasars, are viewed at small angles to the jet axis. BL Lac objects, together with the OVV/HP quasars, form the *blazar* category of AGNs. It should be noted, however, that the existence of two distinct radio morphologies, FR I and FR II (and related bimodal classification of all radio loud objects) doesn't necessary imply bimodal distribution of AGN properties. Specifically, that there is a large luminosity overlap between FR II and FR I objects as well as between BL Lac objects and OVV/HP; that there is no evidence for bimodal distribution of equivalent widths of emission lines in blazars; that there are some radio galaxies which on one side have FR I type radio structure and on another side FR II type radio structure [30]; and, finally, the global spectral properties of blazars seem to form a continuous pattern parameterized by the total blazar luminosity [24].

JET ENERGY DISSIPATION AND PARTICLE ACCELERATION

Rapid variability and the extent of blazar spectra to GeV and TeV energies imply particle acceleration *in situ*. The ultimate source of particle energy is the kinetic and intrinsic energy of a jet. The simplest and most popular model of production of high amplitude short term flares involves collisions of inhomogeneities moving with different velocities down the jet [57,9,26]. If inhomogeneities are ejected by the central engine with bulk Lorentz factors $\Gamma_f > \Gamma_s \gg 1$, separated by a distance Δr_{ej}, they start to collide at a distance

$$r_0 \simeq \frac{c\Delta r_{ej}}{v_f - v_s} \sim \frac{2\Gamma_f^2\Gamma_s^2}{\Gamma_f^2 - \Gamma_s^2}\Delta r_{ej} \tag{5}$$

The collisions are followed by a formation of forward-reverse shock structures, with the shocked plasma enclosed between the shock fronts and moving with the bulk Lorentz factor of the contact discontinuity surface, which for equal rest densities of inhomogeneities is $\Gamma \sim \sqrt{\Gamma_f\Gamma_s}$ (for more general cases see [13,39]). As the collision proceeds, relativistic particles are accelerated and produce non-thermal radiation. For symmetrical inhomogeneities, collisions last

$$t_{coll} = \Gamma t'_{coll} \simeq \frac{\Gamma\lambda'}{v'_f} \sim \frac{\Gamma\lambda'}{c}\frac{\Gamma_f^2 + \Gamma^2}{\Gamma_f^2 - \Gamma^2} \tag{6}$$

where λ' is the radial width of the colliding inhomogeneities and v'_f is the velocity of the faster moving inhomogeneity, both as measured in the contact surface frame. After that time the shocks and the injection of relativistic particles terminate. Thus, in case of a point source, the observer located at $\theta_{obs} \sim 1/\Gamma$ will see the flare which lasts

$$t_{fl} = t_{coll}(1 - \beta\cos\theta_{obs}) \simeq \frac{t_{coll}}{\Gamma^2} \tag{7}$$

provided electrons cool faster than the collision lasts. For the flow which is modulated such that $\Delta r_{ej} \sim \lambda'/\Gamma$, and $\Gamma_f/\Gamma_s \sim$few, Eqs.(5-6) give

$$t_{coll} \sim \frac{r_0}{c} \tag{8}$$

i.e. during the collision the source of radiation doubles its distance from the central object. For sources with finite size, light-travel effects must be included, and then the flare time is $t_{fl} \sim (t'_{coll} + \lambda'_{sh}/c + a/c)/\Gamma$ where a is the cross-sectional radius of the source and λ'_{sh} is its radial width (the width of the layer of the shocked gas enclosed between the forward and reverse shock fronts). However, because $\lambda'_{sh} \sim (2v'_d/c)t'_{coll}$, where v'_d is the shock down-stream velocity, and because effectively in the conical jets $a \leq r/\Gamma$ (no larger area than this can contribute to the observed radiation due to Doppler beaming), the time scale for a source with a finite dimension is of the same order as for the point source.

Efficiency of energy dissipation via collisions of symmetric inhomogeneities is [13,39]

$$\eta_{diss} \simeq 1 - \frac{2\sqrt{\Gamma_f/\Gamma_s}}{1+\Gamma_f/\Gamma_s} \tag{9}$$

Some portion of dissipated energy is converted to the thermal energy of the shocked plasma, and the remaining part is used to accelerate protons and electrons up to relativistic energies. Protons are quite efficiently accelerated by Fermi mechanism in shocks (see reviews by [18,7,38]). Time scale of the acceleration is

$$t'_{acc} \simeq \zeta \left(\frac{c}{v'_{sh}}\right)^2 t'_B \tag{10}$$

where ζ is the ratio of the mean free path for Fermi scatterings to the gyro-radius, v'_{sh} is the velocity of the upstream flow, and

$$t'_B = \frac{2\pi\gamma_p m_p c}{eB'} \tag{11}$$

is the gyro-time. The value of ζ is equal to $u'_B/kw(k)$, where $w(k)$ is the magnetic energy density per unit wavenumber k in the turbulent magnetic field, and u'_B is the total magnetic energy density. For Kolmogorov turbulence spectrum, $w(k) \propto k^{-5/3}$, i.e. the smallest values of ζ are predicted for most energetic protons [5]. Protons accelerated by the Fermi mechanism in strong but non-relativistic shocks have a power-law energy distribution with a slope corresponding to the equal energy per decade of energy.

Electrons can be accelerated by shocks as well, but first they must be preheated to energies $\gamma_{th} \sim (v'_u/c)m_p/m_e$, in order to be scattered freely over the shock front and energized between diverging flows, where v'_u is the upstream flow velocity in the shock front frame. There are several processes which have been suggested to preheat electrons [32,40,54,6,45,17,56]. The most promising scenario is, where electrons are heated by waves induced in the upstream flow by protons reflected from the shock front.

In general, the slope of energy distribution of preheated electrons can be different than the slope of accelerated protons, but those accelerated further up to $\gamma \gg \gamma_{th}$

via Fermi scatterings will have similar slope to that of the protons. The large difference is predicted, however, for maximum energies, which for electrons is much stronger limited by radiative energy losses than for protons.

RADIATION PROCESSES

Electron energy losses

Radiative cooling of relativistic electrons is dominated by synchrotron mechanism and inverse-Compton process. The rate of radiative cooling in the source comoving frame, in which electrons are assumed to have isotropic momentum distribution, is

$$\left|\frac{d\gamma}{dt'}\right|_{rad} \simeq c_1 \gamma^2 u' \tag{12}$$

where $u' \simeq u'_B + u'_{rad<}$, $u'_B = B'^2/8\pi$ is the magnetic energy density, $u'_{rad<} = u'_{rad}[\nu < m_e c^2/h\gamma]$ is the radiation energy density within the frequency range for which scatterings off electrons with energy γ are within the Thomson limit, and $c_1 = 4\sigma_T/3m_e c$. Comparing time scale of electron radiative cooling, $t'_{e,cool} \simeq \gamma/|d\gamma/dt'|_{rad}$, with the collision time scale, $t'_{coll} \sim \Gamma t_{fl}$, one can find that energy, above which energy distribution of electrons steepens due to radiative losses (by unity with respect to the injection slope) is

$$\gamma_c \simeq \frac{1}{c_1 \Gamma u' t_{fl}} \simeq \frac{24}{u'} \frac{1}{(\Gamma/15)(t_{fl}/1\mathrm{day})} \tag{13}$$

Radiation energy density is contributed by both local emission and by external radiation fields. The dominant local contribution to $u'_{rad<}$ for $\gamma \gg 1$ is provided by synchrotron radiation:

$$u'_{syn<} \simeq \frac{L_{syn<}}{2\pi a^2 c \Gamma^4} \tag{14}$$

where $L_{syn<}$ is the apparent luminosity of synchrotron radiation within the Thomson limit ($\nu < \Gamma m_e c^2/h\gamma$). Contribution from the external radiation fields to u'_{rad} is

$$u'_{ext} = \frac{1}{c}\int I' d\Omega' = \frac{1}{c}\int I \mathcal{D}_{in}^{-2} d\Omega \tag{15}$$

where I is the intensity of the incoming external radiation, $\mathcal{D}_{in} = 1/\Gamma(1-\beta\cos\theta_{in})$, and θ_{in} is the angle between the jet axis and an incoming ray. Provided that the dependence of I on θ_{in} is much weaker than the dependence of $\mathcal{D}_{in}$ on θ_{in}, the u'_{ext} is dominated by those external radiation fields which at a distance of the flare production contribute significantly from the side and the front of the jet [60]. Such radiation fields are provided by BEL region and by infrared radiation by hot dust, and from Eq. (15)

$$u'_{ext}(r) \simeq f_2 \Gamma^2 u_{ext}(r) \tag{16}$$

where for the external sources located in the narrow torus at r_{ext}

$$f_2 \simeq \left(1 - \frac{r/r_{ext}}{\sqrt{1 + (r/r_{ext})^2}}\right)^2 \tag{17}$$

Noting that distance of the flare production,

$$r_{fl} \sim ct_{fl}\Gamma^2 \sim 6 \times 10^{17} (t_{fl}/1\mathrm{day})(\Gamma/15)^2 \,\mathrm{cm} \tag{18}$$

is on the order of r_{BEL}, the value of f_2 can be sometimes significantly lower than unity. For scatterings of IR radiation, because $r_{dust} \gg r_{fl}$, we have $f_2 \simeq 1$. Noting that $\nu_{BEL} \simeq 10^{15}$ Hz, $\nu_{IR} \sim 3kT_{dust}/h \simeq 6 \times 10^{13} T_3$ Hz, and that $\nu'_{ext} \simeq \mathcal{D}_{in}^{-1} \nu_{ext} = \sqrt{f_2}\Gamma \nu_{ext}$, one can find that BELs are scattered within the Thomson limit by electrons with energies

$$\gamma < \frac{m_e c^2}{\sqrt{f_2}\Gamma h \nu_{BEL}} \sim \frac{7.9 \times 10^3}{\sqrt{f_2}(\Gamma/15)} \tag{19}$$

while the dust radiation is scattered within the Thomson limit by electrons with energies

$$\gamma < \frac{m_e c^2}{\sqrt{\Gamma} h \nu_{IR}} \sim \frac{1.3 \times 10^5}{T_3 (\Gamma/15)} \,. \tag{20}$$

Proton energy losses

Protons lose energy via synchrotron and inverse Compton radiation at a rate

$$\left|\frac{d\gamma_p}{dt'}\right| \simeq c_2 \gamma^2 u' \tag{21}$$

where $c_2 = (m_e/m_p)^3 c_1$.

Comparing the time scale of proton radiative cooling, $t'_{p,cool} = \gamma_p / |d\gamma_p/dt'|$, with the flare time scale, one can find that only protons with energies larger than

$$\gamma_{p,c}^{(rad)} \simeq \frac{1}{c_2 \Gamma u' t_{fl}} \simeq \frac{1.5 \times 10^{11}}{u'} \frac{1}{(\Gamma/15)(t_{fl}/1\mathrm{day})} \tag{22}$$

can radiate efficiently.

Protons can also lose energy via inelastic collisions with photons and cold ions. Collisions with photons can lead to meson production (photo-meson process) and to direct e^+e^- pair production. Time scales of proton energy losses in these processes are [4]:

$$t_{p\gamma}^{(\pi)\prime} \simeq \frac{5.6 \times 10^{17}}{n_{>}^{(\pi)\prime}} \tag{23}$$

$$t_{p\gamma}^{(e)\prime} \simeq \frac{6.7 \times 10^{19}}{n_{>}^{(e)\prime}} \tag{24}$$

$$t'_{pp} \simeq \frac{2.2 \times 10^{15}}{n'_p} \tag{25}$$

for photo-meson production, pair production, and pp collisions, respectively, where $n_{>}^{(\pi)\prime} = \int_{\nu_{th}^{(\pi)\prime}} n'_\nu \, d\nu'$, $n_{>}^{(e)\prime} = \int_{\nu_{th}^{(e)\prime}} n'_\nu \, d\nu'$, and the threshold photon energies for $p\gamma$ collisions are $\nu_{th}^{(\pi)\prime} \simeq m_\pi c^2/h\gamma_p \simeq 3 \times 10^{22}/\gamma_p$, and $\nu_{th}^{(e)\prime} \simeq 2m_e c^2/h\gamma_p \simeq 2 \times 10^{20}/\gamma_p$.

BLAZAR MODELS

Depending on the dominant mechanism considered for the γ-ray production, blazar models can be divided into three groups:

- SSC models, where production of γ-rays is dominated by Comptonization of locally emitted synchrotron radiation;
- ERC models, where production of γ-rays is dominated by Comptonization of external radiation fields;
- hadronic models, where production of γ-rays is dominated by synchrotron radiation of proton-initiated-cascades (PIC), and/or by synchrotron radiation of protons and muons.

These models are discussed below as applied to OVV/HP quasars and TeV-BL Lac objects.

SSC models

The simplest SSC model is the one-component version, where the radiation observed at any given moment is produced by a source/shock moving along a jet. In the SSC model, the frequency of the γ-ray luminosity peak is located at

$$\nu_H \sim \begin{cases} \gamma_m^2 \nu_L & \text{if } h\nu_L > \gamma_m m_e c^2/\Gamma \\ \gamma_m m_e c^2/h & \text{otherwise} \end{cases} \tag{26}$$

where

$$\nu_L \sim c_B \gamma_m^2 \Gamma B' \tag{27}$$

is the location of the synchrotron peak, γ_m is the location of the break in the electron energy distribution, and $c_B = (2/3\pi)(e/m_e c)$. These equations together with the ratio of the luminosity peaks,

$$\frac{\nu_H L_{\nu_H}}{\nu_L L_{\nu_L}} \simeq \frac{u'_{syn,<}}{u'_B} \tag{28}$$

allow to derive B', Γ, and γ_m.

SSC in OVV/HP quasars

The SSC process can dominate γ-ray production in OVV/HP quasars if

$$\frac{L_{SSC}}{L_{ERC}} \sim \frac{u'_{syn}}{u'_{ext}} > 1 \tag{29}$$

This can be satisfied in OVV/HP quasars only if geometry of the BEL region is such that $f_2 < 10^{-2}$ and if temperature of dust is lower than 300 K, or that $\Gamma < 5$. First condition is difficult to satisfy, because from reverberation mapping, $r_{BEL} \sim r_{fl}$; second condition is in contradiction with observations of near/mid IR radiation in AGNs of radio-lobe dominated quasars. Finally, $\Gamma < 5$ contradicts with VLBI data. Furthermore, one-component SSC model predicts X-ray spectra which are too soft.

SSC in TeV-BL Lac objects

Much more promising are SSC models as applied to BL Lac objects, in particular to the BL Lac objects which are TeV sources [61,63,36,3]. In these objects, Klein-Nishina effects are important. Using Eqs. (26-28), one can find that typically $B' \sim 0.3$ Gauss and $\gamma_m \sim 3\times10^4$ [63]. Using these numbers, Eq. (13) gives $\gamma_c \sim \gamma_m$. This suggests that spectral breaks at peaks are due to effects of cooling; furthermore, the fact that γ_m is only by a factor few lower than $\gamma_{max} \sim h\nu_H/\Gamma m_e c^2$ explains why spectral components in TeV blazars are hard almost up to highest frequencies. Finally, noting that maximum electron energies presumably are determined by the balance of the acceleration time scale and radiative cooling time scale, having $t'_{coll} \sim t'_{cool}$ provides natural explanation for existence of "histeretic" variability patterns observed with both signs in the X-ray band in the spectral index vs. flux diagram [61,62,36,23].

ERC models

In the ERC one-component model the high energy peak is located at

$$\nu_H \sim \xi_1 \Gamma^2 \gamma_m^2 \nu_{ext} \tag{30}$$

while ratio of the peak luminosities is

$$\frac{\nu_H L_{\nu_H}}{\nu_L L_{\nu_L}} \simeq \frac{u'_{ext}}{u'_B} \tag{31}$$

ERC in OVV / HP blazars

When applying ERC model to Q-blazars, it is better not to rely on relation (27). This is not only because ν_L is located in these objects in the spectral range which observationally is poorly covered (far-IR band), but also because there are some observational indications that far-infrared radiation can be strongly contaminated by radiation produced at larger distance in a jet than the high energy flares. These indications are: the low energy break of the synchrotron component is at lower frequencies than the break due to synchrotron-self-absorption on sub-parsec scales [57]; and there is clear trend of decreasing amplitude of the flare with decreasing frequency in the synchrotron component [19,20,69]. However, in order to close a system of equations describing the model, one has to replace one equation by another. Such relationship can be derived by assuming that $\gamma_m = \gamma_c$ [9]. Another useful approximation is to treat as a known observable Γ, instead of u_{ext}. This is because due to unknown geometry of the BEL region and unknown maximum temperature of dust, model errors which can result from using uncertain values of f_2 and T_{dust} can be larger, than resulting from uncertain value of Γ. Alternatively, instead of treating Γ as known, one can make an assumption about equipartition of magnetic fields with relativistic particles. Our preliminary results show that for $\Gamma \sim 15$ both approaches give similar results. Using observables typical of OVV/HP blazars, namely: $\nu_H = 10^{21}$ Hz; $\nu_H L_{\nu_H}/\nu_L L_{\nu_L} = 10$; $t_{fl} = 1$ day; and $\Gamma = 15$, and assuming that the high energy luminosity is dominated by ERC(BEL), we obtain $B' \sim 1$ Gauss; $\gamma_c \sim 70$; $\nu_L \sim 2 \times 10^{11}$ Hz (which actually is below the synchrotron-self-absorption frequency); $\gamma_{max} \sim 4 \times 10^3 \sqrt{\nu_{syn,max}/10^{15}\mathrm{Hz}}$; and $f_2 \sim 0.2$.

Model parameters derived in this manner can be used as "first approximation" parameters for dynamical models intended for a study of time evolution of electron energy distribution. Such models have been recently developed using two kinds of approximations: one is a spherical source approximation by [12,26] and another is a thin shell approximation by [9]. Results of both demonstrate the ability of ERC models to explain the observed spectra and flares of OVV/HP quasars. In addition, these models support the earlier predictions that the SSC radiation component, despite its lower luminosity than the ERC component, can dominate the soft/mid X-ray bands [33,37].

ERC in TeV-blazars

Very little is known about radiative environment in these objects and, so, energy density of external radiation fields must be treated as a free parameter. But there are interesting constraints regarding the level of the IR radiation from dust. This radiation must be very weak, otherwise TeV γ–rays would be absorbed in the pair production process [11]. However, production of TeV component by Comptonization of radiation of dust is still feasible, provided $\Gamma > 15$.

Hadronic models

Hadronic models, which are motivated by theories of particle acceleration, suffer difficulties in explaining the observed electromagnetic spectra and/or short term variability. Proposed for the OVV/HP quasars, models involving proton induced cascades (PIC) [42] predict X-ray spectra which are softer than observed. They also require fine-tuning of model parameters in order to have the location of the radiation deficiency (the "dip" between the low energy and high energy peaks in the broad-band spectra) located at the right frequency in all OVV/HP blazars. Furthermore, there are already several examples of OVV/HP blazars, where X-ray spectra have slopes $\alpha_X < 0.5$ [22,53,64], which cannot be explained in terms of the synchrotron radiation mechanism. This is because synchrotron radiation in the X-ray band requires such energetic electrons, that they must cool efficiently and, therefore, produce spectra with $\alpha_X > 0.5$, even if injected mono-energetically.

From unknown us reasons, no contribution of pp$\rightarrow$ pe$^+$e$^-$ was taken into account in PIC models. The process is about 100 times less efficient per photon than photo-meson one, but this is compensated by a much larger number of photons above the threshold energy, which for pair production is ~ 100 lower than for photo-meson process.

Another hadronic model proposed for OVV/HP blazars is based on the process of inelastic collisions of ultrarelativistic protons with the cold ions. Such process in order to be efficient requires very dense targets and huge bulk Lorentz factor ($\Gamma \gg 10$) of streaming protons. In the paper [2] it is proposed that the dense target is provided by the walls of the funnel formed by geometrically thick disc. The main problem with this model we can envisage is overproduction of soft X-rays, which would be produced due to Comptonization of accretion disk UV photons by cold electrons in a jet This effect can be avoided if in the vicinity of the black hole, up to at least 100 gravitational radii, jet is not yet collimated [59]. But then beamed blazar radiation must be produced at larger distances, probably at $r \sim 10^{17-18}$ cm as the flare time scales suggest.

Hadronic models have been proposed also for TeV-blazars. In these objects the soft spectra of PIC models contrast with the very hard observed spectra even more. This problem is avoided in proposed recently the proton-synchrotron model [1,47]. In such a model high energy spectra are produced directly by protons, just via synchrotron radiation. The model predicts hard spectra and is also attractive, because can explain constant slope of high energy tail of TeV component during high amplitude flux changes [1]. In the model, maximum proton energies $\gamma_{p,max} > 10^{10}/\sqrt{B'/100\mathrm{G}}$ are required in order to satisfy condition $t'_{p,syn}(\gamma_{p,max}) \le t_{fl}\Gamma$.

Another version of the hadronic model has been suggested by Rachen & Mészáros [51]. In their model the bulk Lorentz factor is assumed to be rather low ($\Gamma \sim 3$) and protons with $\gamma_{p,max} > 10^{10}$ lose comparable energies via photo-meson process as via synchrotron mechanism. Following the former, the muons are produced with such energies, that before decay they undergo significant synchrotron energy losses, dominating production of TeV peak. The weak point of both above hadronic models is that in order to accelerate protons up to $\gamma_{p,max} > 10^{10}$ energies, the quantities ζ and v'_{sh}/c (see Eq. [10]) must be pushed to extremes, i.e., should have values 1.

SUMMARY

As analysis of jet energetics and X-ray observations of blazars indicate, plasma in sub-parsec jets can contain from few up to tens of e^+e^- pairs per proton [58,9]. With such a number of pairs energy flux of sub-parsec jets is still dominated by protons, and, therefore, the structure of shocks is determined by proton plasma. Then, one should expect very efficient shock acceleration of protons, with maximum energies as high as $\gamma_p \sim 10^9 - 10^{10}$, as limited by size of the source or balanced by energy losses. Furthermore, very large values of ζ (ratio of the mean free path for Fermi scatterings to gyro-radius) for electrons, 10^{3-6}, as derived for maximum electron energies assuming that for them $t'_{cool} = t'_{acc}$, seem to be consistent with the presence of ultrarelativistic protons, provided the turbulent magnetic field has a Kolmogorov spectrum [5]. On the other hand, very hard X-ray spectra and short variability time scales put severe constraints on radiative role of protons. Does this contradict with theoretical predictions about very efficient acceleration of protons? Not necessary.

The average proton cannot reach more random energy in the shock than $\bar{E}_p \sim (\Gamma'_u - 1) m_p c^2$, where Γ'_u is the bulk Lorentz factor of the upstream flow as measured in the rest frame of the shock front. Intrinsic shocks are at most mildly relativistic, and therefore $\bar{E}_p < m_p c^2$ is expected. Comparing this with the average energy of electrons which, as deduced from hard X-ray spectra of some OVV/HP quasars, is in the range $10 - 100$ MeV, and noting that limited energetics of jets combined with electron emissivity implies n_e/n_p to be at least of the order of 10, one can find that fraction of energy dissipated in the shock and used to accelerate electrons does not have to be much lower than energy channeled to protons. This, combined with the fact that radiative efficiency of electrons is much larger than of protons, can explain negligible contribution of the proton related processes to the observed spectra.

Acknowledgments: This work has been supported in part by the Polish KBN grant 2P03D 00415.

REFERENCES

1. Aharonian F.A., *New Astronomy* **5**, 377 (2000).
2. Bednarek W., *ApJ* **402**, L29 (1993).
3. Bednarek W., and Protheroe R.J., *MNRAS* **310**, 577 (1999).
4. Begelman M.C., Rudak B., and Sikora M., *ApJ* **362**, 38 (1990).
5. Biermann P.L., and Strittmater P.A., *ApJ* **322**, 643 (1987).
6. Blackman E.G., *ApJ* **456**, L87 (1996).
7. Blandford R.D., and Eichler D., *Physics Reports* **154**, 1 (1987).
8. Blandford R.D., and Levinson A., *ApJ* **441**, 79 (1995).
9. Błażejowski M., Sikora M., Moderski R., and Madejski G.M., *ApJ* **545**, 107 (2000).
10. Bottorff M., Korista K.T., Shlosman I., and Blandford R.D., *ApJ* **479**, 200 (1997).

11. Celotti A., Fabian A.C., and Rees M.J., *MNRAS* **293**, 239 (1998).
12. Chiaberge M., and Ghisellini G., *MNRAS* **306**, 551 (1999).
13. Daigne F., and Mochkovitch R., *MNRAS* **296**, 275 (1998).
14. Dar A., and Laor A., *ApJ* **478**, L5 (1997).
15. Dermer C.D., and Schlickeiser R., *ApJ* **416**, 458 (1993).
16. Dermer C.D., and Chiang J., *New Astr.* **3**, 157 (1998).
17. Dieckmann M.E., McClements K.G., Chapmann S.C., Dendy R.O., and Drury L.O'C., *A&A* **356**, 377 (2000).
18. Drury L. O'C., *Rep. Prog. Phys.* **46**, 973 (1983).
19. Edelson R., *ApJ* **401**, 516 (1992).
20. Edelson R., and Malkan M.A., *ApJ* **323**, 516 (1987).
21. Emmering R.T., Blandford R.D., and Shlosman I., *ApJ* **385**, 460 (1992).
22. Fabian A.C., Iwasawa K., Celotti A., Brandt W.N., McMahon R.G., and Hook I.M., *MNRAS* **295**, L25 (1998).
23. Fossati G., Celotti A., Chiaberge M., Zhang Y.H., Chiapetti L., Ghisellini G., Maraschi L., Tavecchio F., Pian E., and Treves A., *ApJ* **541**, 166 (2000).
24. Fossati G., Maraschi L., Celotti A., Comastri A., and Ghisellini G., *MNRAS* **299**, 433 (1998).
25. Gaidos J.A. et al., *Nature* **383**, 319 (1996).
26. Ghisellini G., *Blazar Demographics* ASP Conference Series, eds. C.M. Urry and P. Padovani, in press (astro-ph/0011356).
27. Ghisellini G., and Madau P., *MNRAS* **280**, 67 (1996).
28. Ghisellini G., and Maraschi L., *ApJ* **340**, 181 (1989).
29. Ghisellini G., Padovani P., Celotti A., and Maraschi L., *ApJ* **407**, 65 (1993).
30. Gopal-Krishma, and Wiita P.J., *A&A* **363**, 507 (2000).
31. Hardcastle M.J., and Worrall D.M., *MNRAS* **309**, 969 (1999).
32. Hoshino M., Arons J., Gallant Y.A., and Langdon A.B., *ApJ* **390**, 454 (1992).
33. Inoue S., and Takahara F., *ApJ* **463**, 555 (1996).
34. Komissarov S.S., and Falle S.A.E.G., *MNRAS* **288**, 833 (1997).
35. Königl A., *ApJ* **243**, 700 (1981).
36. Kirk J.G., Rieger F.M., and Mastichiadis A., *A&A* **333**, 452 (1998).
37. Kubo H. et al., *ApJ* **504**, 693(1998).
38. Kuijpers J., *Plasma Astrophysics*, European Astrophysical Doctoral Network VII, eds. C. Chiuderi, G. Einaudi (1995).
39. Lazzati D., Ghisellini G., and Celotti A., *MNRAS* **309**, L13 (1999).
40. Levinson A., *MNRAS* **278**, 1018 (1996).
41. Macomb D.J., et al., *ApJ* **449**, L99 (1995).
42. Mannheim K., and Biermann P.L., *A&A* **253**, L21 (1992).
43. Marscher A.P., and Gear W.K., *ApJ* **298**, 114 (1985).
44. Mattox J.R., et al., *ApJ* **476**, 692 (1997).
45. McClements K.G., Dendy R.O., Bingham R., Kirk J.G., and Drury L.O'C., *MNRAS* **291**, 241 (1997).
46. Murray N., and Chiang J., *ApJ* **474**, 91 (1997).
47. Mücke A., and Protheroe R.J., *Astropart. Phys.* in press (astro-ph/0004052).
48. Nicastro F., *ApJ* **530**, L65 (2000).

49. Peterson B.M., *PASP* **105**, 247 (1993).
50. Petry D. et al., *ApJ* **536**, 742 (2000).
51. Rachen J.P., and Mészáros P., *Phys. Rev.* **D58**, 123005 (1998).
52. Rees M.J., *MNRAS* **184**, P61 (1978).
53. Reeves J.N., et al., *A&A* **365**, L116 (2000).
54. Romanova M.M., and Lovelace R.V.E., *A&A* **262**, 26 (1992).
55. Sambruna R.M., et al., *ApJ* **538**, 127 (2000).
56. Shimada N., and Hoshino M., *ApJ* **543**, L67 (2000).
57. Sikora M., Begelman M.C., Rees M.J., *ApJ* **421**, 153 (1994).
58. Sikora M., and Madejski G.M., *ApJ* **534**, 109 (2000).
59. Sikora M., Madejski G.M., Moderski R., and Poutanen J., *ApJ* **484**, 108 (1997).
60. Sikora M, Sol H., Begelman M.C., and Madejski G.M., *MNRAS* **280**, 781 (1996).
61. Takahashi T., et al., *ApJ* **470**, L89 (1996).
62. Takahashi T., et al., *ApJ* **543**, L124 (2000).
63. Tavecchio F., Maraschi L., and Ghisellini. G., *ApJ* **509**, 608 (1998).
64. Tavecchio F., et al., *ApJ* **543**, 535 (2000).
65. Ulrich M.-H., Maraschi L., and Urry C.M., *ARAA* **35**, 445 (1997).
66. Urry C.M., and Padovani P., *PASP* **107**, 803 (1995).
67. von Montigny C., et al., *ApJ* **440**, 525 (1995).
68. Wagner S., et al., *ApJ* **454**, L97 (1995).
69. Wehrle A.E., et al., *ApJ* **497**, 178 (1998).
70. Woźniak P.R., Zdziarski A.A., Smith D., Madejski G.M., and Johnson W.N., *MNRAS* **299**, 449 (1998).